

ENERGYPLUS: A NEW-GENERATION BUILDING ENERGY SIMULATION PROGRAM

Drury B. Crawley
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0121

Linda K. Lawrie
U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
Champaign, Illinois 61821

Frederick C. Winkelmann
Lawrence Berkeley National Laboratory
Berkeley, California 94720

Curtis O. Pedersen
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

ABSTRACT

Many of the popular building energy simulation programs around the world are reaching maturity—some use simulation methods (and even code) that originated in the 1960s. For more than two decades, the U.S. government supported separate development of two hourly building energy simulation programs, BLAST and DOE-2. Designed in the days of mainframe computers, expanding their capabilities further became difficult, time-consuming, and prohibitively expensive. At the same time, significant advances in analysis and computational methods and power occurred—providing an opportunity for significant improvement in these tools.

In 1996, the U.S. Department of Energy (DOE) began developing a new building energy simulation tool called EnergyPlus. This work built on development experience with two existing programs: DOE-2 and BLAST. EnergyPlus includes a number of innovative simulation features—such as variable time steps, user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation—and input and output data structures tailored to facilitate third party module and interface development. Other planned simulation capabilities include multizone airflow, and electric power and solar thermal and photovoltaic simulation. Beginning in late 1999, a series of five beta test versions were released. Version 1.0 of EnergyPlus was released in April 2001.

1. INTRODUCTION

For more than twenty years, the U.S. government supported separate development of two major building energy simulation programs, DOE-2 and BLAST. BLAST

(Building Systems Laboratory 1999), sponsored by the U.S. Department of Defense (DOD), has its origins in the NBSLD program developed at the U.S. National Bureau of Standards (now NIST) in the early 1970s. DOE-2 (Winkelmann et al 1993), sponsored by the U.S. Department of Energy (DOE), has its origins in the Post Office program written in the late 1960s for the U.S. Post Office. The main difference between the programs is load calculation method—DOE-2 uses a room weighting factor approach while BLAST uses a heat balance approach. Both programs are widely used throughout the world.

Each program comprises hundreds of subroutines working together to simulate heat and mass energy flows throughout a building. In some cases, subroutines in DOE-2 were more accurate. In other cases, subroutines in BLAST were more accurate. In both cases, simulation methodologies are often difficult to trace due to decades of development (and multiple authors). Often, this results in ‘spaghetti code’ with data and subroutines for a particular simulation capability spread throughout the program. To modify either program, a developer must have many years experience working within the code, knowledge of code unrelated to their task (because of the spaghetti), and (often for sponsors) an extraordinary investment of time and money.

Many people questioned why the U.S. government was supporting two separate (and comparable capability) programs. In 1996, DOE took the initiative and began developing a new program named EnergyPlus. The EnergyPlus team includes U. S. Army Construction Engineering Research Laboratory, University of Illinois, Lawrence Berkeley National Laboratory, Oklahoma State University, GARD Analytics, Florida Solar Energy Center and DOE. In this paper, we present an overview of the organization and capabilities of EnergyPlus and explain the rationale and structure behind the overall program.

2. WHAT IS ENERGYPLUS?

Because of 20+-year-old code, DOE-2 and BLAST became too expensive to maintain, modify and enhance. When we began developing EnergyPlus, we thought that we could create a ‘best of’ program—combining modules from the two programs—without starting from scratch. After initial development work, we determined that EnergyPlus would cost less to develop, be released faster, and be easier to modify and extend if we wrote all new code.

Thus, EnergyPlus is an all-new program based on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus comprises completely new, modular, structured code written in Fortran 90. It is a simulation engine—there is no interface. Figure 1 shows screen images of EnergyPlus utilities and example results. Both BLAST and DOE-2 have successfully attracted third-party developers to create user interfaces and new modules. During EnergyPlus beta testing we worked with these same developers on new simulation modules or to develop their own user interfaces.

One of the main goals we set for developing EnergyPlus was to create a well-organized, modular structure to facilitate adding features and links to other programs. In evaluating programming languages, we found we had two choices—move to C/C++ or stay with Fortran. Despite the advantages of the structure and object-orientation of C/C++, we decided to select Fortran 90 as the programming language for EnergyPlus.

We began working on EnergyPlus by modularizing (restructuring) code from the heat balance engine in BLAST. Using a process we call Evolutionary Reengineering (ER), we incrementally moved the program from old unstructured legacy code to new modular code by incorporating new code with old. The existing code still worked with user input data, and was extended to generate parameters needed by the new code modules. In this way new modules were verified without having to completely replace the entire functional capability of the old program with new code before it was tested. As the process proceeded, the parameters supplied by old routines were replaced by new routines and data structures. This made the transition evolutionary and permitted a smooth transition with a greater capability for verification testing.

3. ENERGYPLUS STRUCTURE AND CAPABILITIES

In recent workshops on needs for energy tools, there was strong consensus that a more flexible and robust tool with additional capabilities is needed. Recurrent simulation needs throughout both workshops were design, environment, economics, and occupant comfort and safety.

Designers wanted tools that provide answers to very specific questions during design. They wanted tools that provide the highest level of simulation accuracy and detail reasonably possible but that don’t get in the user’s way. One of the highest priorities was an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction.

In response to these findings, we decided that integrated simulation should be the underlying concept for EnergyPlus—loads calculated (by a heat balance engine) at a user-specified time step (15-minute default) are passed to the building systems simulation module at the same time step. The building systems simulation module, with a variable time step (down to seconds), calculates heating and cooling system and plant and electrical system response. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures if necessary.

By using an integrated solution technique in EnergyPlus, the most serious deficiency of the BLAST and DOE-2 sequential simulations can be solved—inaccurate space temperature prediction due to no feedback from the HVAC module to the loads calculations. Accurate prediction of space temperatures is crucial to energy efficient system engineering—system size, plant size, occupant comfort and occupant health are dependent on space temperatures.

Integrated simulation also allows users to evaluate a number of processes that neither BLAST nor DOE-2 can simulate well, including realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

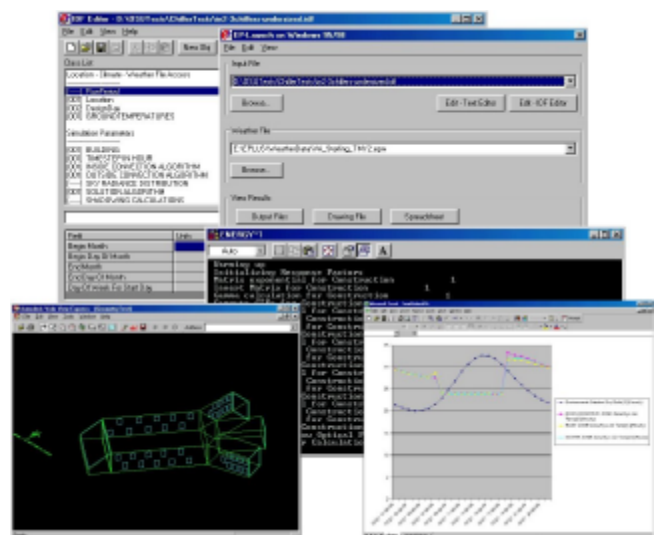


Fig. 1. Screen Images of EnergyPlus Utilities and Results

Figure 2 shows the overall program structure—EnergyPlus has three basic components—a simulation manager, a heat and mass balance simulation module, and a building systems simulation module. The simulation manager controls the entire simulation process.

A new building systems simulation manager handles communication between the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans, and other equipment/components. The building systems simulation manager also controls interaction and data exchange between EnergyPlus and SPARK (Buhl et al. 1993) and TRNSYS (SEL 1999) simulations. Gone are the hardwired ‘template’ systems (VAV, Constant Volume Reheat, etc.) of DOE-2 and BLAST—replaced by user-configurable heating and cooling equipment components formerly within the template. This gives users much more flexibility in matching their simulation to the actual system configurations. The building systems simulation module also manages data communication between the HVAC modules, input data, and output data structures.

A comparison of major features and capabilities of EnergyPlus, BLAST, and DOE-2 is shown in Tables 1, 2, and 3. Table 1 shows general features, Table 2 load calculation features, and Table 3 HVAC features. The simulation manager, heat balance simulation manager, and building systems simulation manager are described below.

3.1 Heat and Mass Balance

As noted earlier, the underlying building thermal zone calculation method in EnergyPlus is a heat balance model. The fundamental assumption of heat balance models is that air in each thermal zone can be modeled as well stirred with uniform temperature throughout.

In addition to the basic heat and mass balance engine from BLAST, we created three new modules based on capabilities within DOE-2: daylighting and electric lighting illumination, WINDOW 5-based fenestration, and anisotropic sky. The daylighting module calculates hourly interior daylight illuminance, glare from windows, electric lighting controls, and calculates electric lighting reduction for the heat balance module. The fenestration module includes capabilities from the soon-to-be released WINDOW 5—accurate angular dependence of transmission and absorption for both solar and visible radiation, and temperature-dependent U-value. Users can enter a layer-by-layer window description or choose windows from the library (conventional, reflective, low-e, gas fill, electrochromic). EnergyPlus can also simulate movable interior and exterior window shades. The WINDOW 5

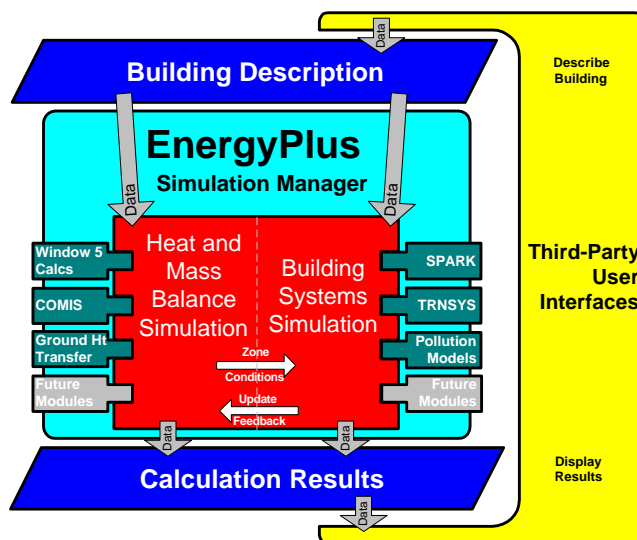


Figure 2. Overall EnergyPlus Structure

algorithms also account for coatings and framing elements. The sky model includes non-isotropic radiance and luminance distribution throughout the sky, which improves calculation of diffuse solar on tilted surfaces (walls and sloped roofs). Strand et al (1999) provide more information on the heat and mass balance implementation in EnergyPlus.

3.2 Building Systems Simulation

After the heat balance manager completes simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. EnergyPlus does not use a sequential simulation method (first building loads, then air distribution system, and then central plant) as found in DOE-2 and BLAST. Instead EnergyPlus uses loops throughout the building systems simulation manager—primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings and eventually will simulate head and thermal losses that occur as fluid moves in each loop. Unlike DOE-2 and BLAST, EnergyPlus has no hardwired ‘template’ systems. Instead, we developed equivalent input file templates for the each of the major system types in BLAST and DOE-2. These templates provide users with a starting point for system configurations that differ from ‘default’ configurations. Fisher et al (1999) provide additional information about the approach to building systems simulation in EnergyPlus. In the longer term, EnergyPlus users will have more systems and equipment options through a link to SPARK (Buhl et al. 1993), an equation-based simulation tool that includes a library of HVAC components. Developers and

TABLE 1. COMPARISON OF GENERAL FEATURES AND CAPABILITIES

General Feature	DOE-2	BLAST	EnergyPlus
Integrated, Simultaneous Solution <ul style="list-style-type: none"> • Integrated loads/systems/plant • Iterative solution • Tight coupling 	No	No	Yes
Multiple Time Step Approach <ul style="list-style-type: none"> • User-defined time step for interaction between zones and environment (15-minute default) • Variable time-step for interactions between zone air mass and HVAC system (≥ 1 minute) 	No	No	Yes
Input Functions <ul style="list-style-type: none"> • Users can modify code without recompiling 	Yes	No	Yes
Reporting Mechanism <ul style="list-style-type: none"> • Standard reports • User-definable reports • Visual surface output 	Yes Yes No	Yes No No	Yes Yes Yes

TABLE 2. COMPARISON OF LOADS FEATURES AND CAPABILITIES

Loads Feature	DOE-2	BLAST	EnergyPlus
Heat Balance Calculation <ul style="list-style-type: none"> • Simultaneous calculation of radiation and convection processes each time step 	No	Yes	Yes
Interior Surface Convection <ul style="list-style-type: none"> • Dependent on temperature and air flow • Internal thermal mass 	No Yes	Yes Yes	Yes Yes
Moisture Absorption/Desorption <ul style="list-style-type: none"> • Combined heat and mass transfer in building envelopes 	No	No	Yes
Thermal Comfort <ul style="list-style-type: none"> • Human comfort model based on activity, inside drybulb, humidity, and radiation 	No	Yes	Yes
Anisotropic Sky Model <ul style="list-style-type: none"> • Sky radiance depends on sun position for better calculation of diffuse solar on tilted surfaces 	Yes	No	Yes
Advanced Fenestration Calculations <ul style="list-style-type: none"> • Controllable window blinds • Electrochromic glazing 	Yes	No	Yes
WINDOW 5 Calculations <ul style="list-style-type: none"> • More than 200 window types—conventional, reflective, low-E, gas-fill, electrochromic • Layer-by-layer input for custom glazing 	No No	No No	Yes Yes
Daylighting Illumination and Controls <ul style="list-style-type: none"> • Interior illuminance from windows and skylights • Step, dimming, on/off luminaire controls • Glare simulation and control • Effects of dimming on heating and cooling 	Yes	No	Yes

TABLE 3. COMPARISON OF HVAC FEATURES AND CAPABILITIES

HVAC Systems and Equipment Feature	DOE-2	BLAST	EnergyPlus
Fluid Loops <ul style="list-style-type: none"> Connect primary equipment and coils Hot water loops, chilled water and condenser loops, refrigerant loops 	No	No	Yes
Air Loops <ul style="list-style-type: none"> Connect fans, coils, mixing boxes, zones 	No	No	Yes
User-configurable HVAC systems	No	No	Yes
High-Temperature Radiant Heating <ul style="list-style-type: none"> Gas/electric heaters, wall radiators 	No	Yes	Yes
Low-Temperature Radiant Heating/Cooling <ul style="list-style-type: none"> Heated floor/ceiling Cooled ceiling 	No	No	Yes
Atmospheric Pollution Calculation <ul style="list-style-type: none"> CO₂, SO_x, NO_x, CO, particulate matter and hydrocarbon production On-site and at power plant Calculate reductions in greenhouse gases 	Yes	Yes	Yes
SPARK link	No	No	Yes
TRNSYS link	No	No	Yes

advanced users will be able to easily build complex new HVAC models with SPARK. A similar link is under development to the TRNSYS simulation model (SEL 2000), which will provide users with system/plant, photovoltaic, and solar thermal simulation models.

4. INPUT, OUTPUT, AND WEATHER DATA

EnergyPlus input and output data files are designed for easy maintenance and expansion and in order to accept simulation input data from other programs—but are not intended to be the main interface for typical end-users. We expect most users will use EnergyPlus through an interface from a third-party developer. To make it easy for current DOE-2 and BLAST users to move to EnergyPlus, the team has written utilities that convert BLAST and DOE-2 input to the new EnergyPlus input structure.

The EnergyPlus input file is free format with this basic syntax:

object, data, data, data, . . . , data;

‘Object’ is a pre-defined word representing a building component, such as SURFACE, MATERIAL, LIGHTING, SYSTEM, HEATING COIL, and BOILER. This is

followed by a list of data values and ends with a semicolon.

These data describe performance characteristics and intended use for that object in the simulation. Unlike BLAST and DOE-2, the input file must explicitly include all information—there are no default assumptions.

Output reports include standard output (user specified variables at specified time intervals), one time output (such as input echo, input verification and interim calculations), and visual surface output (including DXF outputs). Because the data structure is simple and comma-separated, output post-processors or spreadsheet programs can easily read the data and create more elaborate reports. One drawback of our simple file format is that the output files can become very large.

The other major data input is weather—which includes basic location information and much of the same data in the TMY2 weather data set developed by NREL. More information on the weather data format is contained in Crawley, Hand and Lawrie (1999).

All the EnergyPlus data files have simple self-contained formats. By working with third party interface developers early, we will keep these files simple and easy to use by other programs that building designers use.

5. TESTING

A critical part of EnergyPlus development has been comparative and analytical testing and validation. Basic loads algorithms have been tested using the ASHRAE Standard 140P (ASHRAE 2000) series of tests that is based on IEA BESTest. Results show that EnergyPlus provides good agreement with other simulation programs. Testing results and methodologies are available to users as part of the EnergyPlus documentation on our web site.

6. UP TO RELEASE 1.0 AND BEYOND

The initial working version of EnergyPlus, or alpha version, was completed in December 1998 for internal testing by the team. In May 1999, a first internal version for testing became available to developers. In December 1999, the first beta test version of EnergyPlus was released for general testing by potential users (followed by 4 other betas). EnergyPlus version 1.0 was released in April 2001.

In mid 2001, we will begin planning for the second release of EnergyPlus based on new features suggested by users, developers, and the development team. We plan to release updates to EnergyPlus on an approximately 18-month release cycle. New planned capabilities include electrical system simulation, solar thermal modules, complex daylighting systems, more HVAC equipment and system types, and better calculation of infiltration, natural ventilation, multizone airflow, and air pollutant transport.

7. SUMMARY

EnergyPlus is a new generation building energy simulation program that builds on the strengths of BLAST and DOE-2. Written in Fortran 90, it is a structured, modular program that will be easier to maintain, update, and extend. EnergyPlus not only combines the best features of the BLAST and DOE-2 programs, but also represents a significant step forward in terms of computational techniques and program structures. Connectivity and extensibility were overriding objectives in the design and development process—ensuring broader participation in program enhancement and facilitate third party interface and module development. Beginning with a first beta version in late 1999, EnergyPlus went through extensive testing throughout 2000 and early 2001. In April 2001, DOE released version 1.0 of EnergyPlus. Up to date information on EnergyPlus is provided on the EnergyPlus web site (see web resources below).

8. REFERENCES

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WEB RESOURCES

Information on EnergyPlus including schedule, availability of beta releases, documentation, licensing, programming standards, and other documentation:

http://www.eren.doe.gov/buildings/energy_tools/energyplus

Web-based directory of more than 200 building-related software tools from around the world:

http://www.eren.doe.gov/buildings/tools_directory/